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The Growth of Fire Science

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SUMMARY

The growth of man's knowledge of fire is followed from Paleolithic times to the present. Until 1900, the fundamentals of fire science, Mathematics, Physics, and Chemistry, were in their formative years. During the period 1900 - 1950 the needed basic sciences were further developed and a few fire phenomena were clarified in a scientific way. The developments during these periods are briefly described. The period of rapid growth of fire science, 1950 to the present, is considered in two respects: the developed fire science itself, and the administrative arrangements in the United States that made these developments financially possible.

INTRODUCTION

The Plenary Lecture for this Symposium on Advances in Fire Physics has a title which potentially encompasses all that will be said hereafter. This cannot be my intent. So let me indicate what I will try to do. In the first place, the title is: "*Growth* of Fire Science", not "*History* of Fire Science". The presentation will neither be sufficiently comprehensive nor scholarly to be called "History of:", second, the title is "Growth of Fire *Science*", not the "Growth of Fire *Physics*", because it is perhaps important to look at "Fire Physics" in the larger perspective of "Fire Science". Finally, the only Fire Science Growth that I know from personal experience is that in the United States. I wish, therefore, to apologize immediately to my foreign colleagues, and especially to our honored fire scientist from the United Kingdom, Dr. Phillip Thomas, for presenting a less than adequate description of developments abroad.

Nonetheless, I will proceed to present a picture of the Growth of Fire Science as seen from the United States, with the hope that similar presentations will be written abroad, so that some day a real History of Fire Science can be written.

EARLY FIRE SCIENCE

There is a tendency for fire research workers to feel that Fire Science is only some fifteen to twenty-five years old. All that went before was empirical. And in a certain modern sense, this is correct. However, Newton was quite correct when he noted that his spectacular scientific progress was only possible because he could "stand on the shoulders of giants". So let me start by noting a few of the things that we fire scientists owe to those who came before.

The date and circumstances of the first discovery of the usefulness of fire is lost in prehistory [1]. No men without fire have ever been found. In paleolithic times there were tribes of men who did not know how to make fire. They carried fire with them — never letting it go out. Those who did know how to make fire rubbed sticks together, eventually driven by a hand-operated bowstring. No doubt the discovery of iron and its use in shaping flint tools showed the sparks which led to "flint on steel" as a fire making device, which remains today as an effective gas lighter. Although the "burning glass", the lens, was known very early, it never became generally useful. The phosphorus–sulfur match wasn't invented until about 1830, and that too is ignited by mechanical friction.

Also lost in obscurity is the discovery of fire extinguishment by water. In fact, this may well have been known by observing the effect of rain, even before the value of fire itself was understood. However, the use of a stream of water for fire extinguishment dates from the second century B.C. [1].

Perhaps none of this should be called "Fire Science". It was certainly empirical. However, these ancients understood, but never formalized, the fire triangle. They certainly knew that the failure to replenish the fuel put the fire out; that "smothering" and "water" were equally effective. However, it could not have been until oxygen was discovered by the Chinese [1] about 800 A.D. (they observed that air was made up of two components, one of which supported combustion while the other did not) that the reasons for the fire triangle could have been known.

In fact, the useful discovery of oxygen did not occur until 1771 (by Scheele in Sweden), and its intimate connection with combustion was not appreciated until the work of Lavoisier (1777 in France).

It was about this time that a rash of serious theater fires in Paris caused the government to commission Gay-Lussac [2] to study what could be done about it. He discovered the phenomena of fire retardancy, and by testing all the chemicals in his stockroom discovered essentially all the fire retardant elements known today. The modern science of fire retardants [3] rests still largely in how to apply them rather than exactly how they do their job. Various attractive "explanations" are available, but none is able to predict with certainty to what degree which substance will retard fire in a new material.

THE GROWTH OF SCIENCE

Just what is "Fire Science"? It is certainly not a basic science like Physics or Chemistry. On the other hand, it is not the accumulated know-how required to run an effective fire department. I will use the term to mean the organized knowledge of fire in terms of the basic sciences.

Like fire itself, science grows exponentially. During the nineteenth century the knowledge of Physics, Chemistry, and Mathematics grew to the point that it could begin to be applied to fire. The mechanics of Newton was developed to include the mechanics of continua. Thus the conservation of mass,

$$\rho_{,t} + (\rho v_i)_{,i} = 0 \tag{1}$$

and the Navier–Stokes [4] equations (conservation of momentum)

$$\rho \frac{dv_i}{dt} = -p_{,i} + \tau_{ji,j} + \rho g_i \tag{2}$$

where

$$\tau_{ji} = \mu(v_{i,j} + v_{j,i}) - \frac{2}{3}\mu v_{k,k}\delta_{ij} \tag{3}$$

became available.

Of course the mere expression of these ideas discloses the advanced nature of mathematical analysis that had to be brought into existence. In fact, because of their mathematical complexity, only relatively simple fluid mechanic problems had been solved by 1900; and most of these were solved for a perfect fluid, *i.e.*, a fluid without viscosity. In fact, as we all know too well, these equations still defy man's powers of analysis when we encounter the ever-present turbulent flows.

During this same period, the ideas of energy and its transformations underwent a profound change. Caloric slowly gave way to various forms of internal energy, and the possible transformations [5, 6] were organized under the theory of thermodynamics. Thus, by 1900 the idea of conservation of energy was well developed, as were many of the simpler applications of it to physical and chemical processes. The application of the conservation of energy to heat conduction in solids was developed early in the century by Fourier [7] and others.

$$\rho C_p T_{,t} = (kT_{,i})_{,i} + Q_{\text{reaction}}. \tag{4}$$

This included heat release by chemical reactions in solids. The extension of this work to heat transfer and chemical reactions in liquids and gases was so difficult that almost no progress was made by the end of the century; and of course the analysis of fire problems was out of the question.

Again, it was early in the nineteenth century, under Dalton (1808), that the atomic theory of chemical reactions was well developed. The atomic weights and stoichiometric coefficients followed. The general theory of thermodynamics covered transformations of chemical reaction energies. It was not until the end of the century that

J. Willard Gibbs [8] (1876) placed chemical equilibrium on a firm thermodynamic basis. Also at this time the first real progress was made with chemical kinetics. Van't Hoff [9] (1884) established the normal chemical kinetic ideas and developed the famous formula for reaction rates,

$$\frac{dC_s}{dt} = A Y_s^n Y_r^m \exp(-E/RT). \tag{5}$$

Arrhenius [10] under whose name this equation is usually specified, derived it from the kinetic theory of gases on the assumption that a molecule had to have an energy at least equal to E, the activation energy, before a reaction could occur.

In 1883, Osborne Reynolds [81], at Manchester University, built apparatus with water flowing through a glass pipe. By use of a central dye stream he discovered that the known jump in flow resistance coincided with the breakup of the dye filament, *i.e.*, by the replacement of the laminar flow with highly confused flow — namely, turbulent. Thus was initiated the understanding of the reason why so many flow fields in engineering and fire are analytically intractable.

Finally, electrical science had reached a fairly advanced stage. While fire involves rather limited electrical effects of importance, the modern electrical instrumentation is essential for the development of all the other aspects of fire science.

By 1900, then, nearly all the basic developments required for the start of fire science were on hand. (Only the electronic computer was completely missing.) However, fire science had hardly started, because persons with a scientific bent worked in other areas of science, while the fire practitioner was busy with new pumps, new hoses, and new engines. In fact, about the only fire science in evidence was Malard and Le Chatelier's [11] work on flame speed in gas mixtures,

$$S = \left(\frac{kW(T_f - T_i)}{\rho^2 C_p (T_i - T_o)}\right)^{1/2} \tag{6}$$

and Faraday's [12] Christmas Lectures for Children, on the Candle.

THE FIRST HALF OF THE TWENTIETH CENTURY

Science continued its exponential growth. The century opened with Prandtl's [13] boundary layer theory. The physical observation that a rapid adjustment was made in the fluid motion near a solid surface in order to satisfy the surface boundary condition of no slip, could be exploited to get useful approximate solutions to the Navier–Stokes equation. This idea, extended by two-timing and singular perturbation methods [14], has made it possible to solve a considerable number of otherwise intractable problems. Thus it became clear that most fluid mechanic problems can be understood completely if only the appropriate equations can be solved. The first two decades were used mostly in solving elasticity [15] and incompressible flow [16] problems of many kinds. The next two decades added heat transfer problems [17], and the fifth decade covered many compressible flow problems under the impetus, first, of ballistics requirements of World War II, and thereafter the problems of high speed aircraft [18].

It was during the 1940's that the mathematical expressions required for the solution of general fire problems were first written by Eckart [19] and *via* kinetic theory by Hirshfelder [20] *et al.*

Conservation of species:

$$\rho \frac{dY_s}{dt} + (\rho D Y_{,i})_{,i} = W_s . \tag{7}$$

Conservation of energy:

$$\rho \frac{dh}{dt} + \left(\frac{k}{C_p} h_{,i}\right)_{,i} + Q_{\text{reaction}} + Q_{\text{radiation}} = 0, \tag{8}$$

where the species creation rate is given by: (see eqn. (5))

$$W_s = \frac{dY_s}{dt} = \frac{M_s}{\rho} \frac{dC_s}{dt} . \tag{9}$$

While these general developments in the exact mathematical expression for the flow of multicomponent reacting fluids were occurring, all the other sciences were making even more remarkable advances.

Most advances in fluid mechanics were directed toward aircraft problems. The work on shock waves initiated by World War II clarified the relationship between detonations and deflagrations [21, 22]. While detonations always traveled at the sound speed in the hot reaction products, proven both experimentally and analytically, the efforts to improve Malard and Le Chatelier's flame spread formula [23] were interesting but not very productive.

The fact that physically correct equations must be dimensionally homogeneous was no doubt intuitively known for a long time. Its formalization by Buckingham [24] and Bridgeman [25], and the similarity proof by use of the general equations of fluid mechanics made it clear that even though solutions of these equations were hopelessly complex, especially if the flow was turbulent, nonetheless, the desired answer in dimensionless form must be a unique function of a few dimensionless independent variables. With this, exact model testing is possible and all data can be generalized.

Dimensionless correlations became the backbone of a great upsurge in the science of heat transfer [17]. Much of the conductive, convective and phase change heat transfer data are of direct use in fire studies. Heat transfer sections appeared in the various professional societies during this period.

While the physicists were clarifying the laws of radiation, emission, absorption, etc., engineers were learning how to calculate the radiative heat transfer between bodies, and from flames to bodies. Hottel's work [26] is especially important because it was directed toward furnace performance, and a furnace is a fire in an enclosure, albeit a special controlled one.

In chemical kinetics, it became clear that the simple approach of Van't Hoff [9] was not adequate for many reactions. The introduction of the idea of the chain reaction by Bodenstein [27] (1913) and its further development by Semenoff [28] (1930) answered many of the questions left by the earlier theory.

These advances in chemical kinetics were a great spur to the chemical study of combustion reactions. The science of combustion thus came to life about 1928 at the time of the first combustion symposium. While many of the combustion science concerns were appropriately chemical in nature, it is noteworthy that the very first combustion symposium contained the paper by Burke and Shumann [29], in which what is now generally known as the Swab–Zeldovich transformation was used successfully to solve a simple case of laminar diffusion flame.

During the first part of this century studies of ignition led to the understanding of the importance of the rate of energy release, the rate of heat loss to the environment, and the rate of energy feedback. The books by Jost [30] (1935), Lewis and Von Elbe [31], and Frank-Kaminetsky [32] summarized much of the combustion work that would be applicable to fire.

During this first half-century important evolutionary developments were occurring in the fire fighting and fire protection fields. Various laboratories were started in various countries. In the United States, major fire test laboratories appeared — Factory Mutual, and Underwriters Laboratories. The Bureau of Standards started a fire program, and Ingberg [33] (1928) presented his important work on fire loads.

Very little fire science was involved, however. Bamford, Crank and Millan [34] (1945), using numerical techniques, studied the combustion of wood. Also, the development of the fire plume theory occurred during World War II, when Taylor [35, 36] analyzed the potential effectiveness of fires placed along military airport runways in dispersing the sometimes very dense English fog.

THE ERA OF MODERN FIRE SCIENCE (1950 - PRESENT)

As always, the growth has been exponential. This means not only that the end of the period is filled with progress, but also the beginning is painfully slow. Hirshfelder *et al.* [37] and von Karman [38] had developed a general theory of flame spread through gases capable of including, correctly, the effect of the real chemistry, if known. Unfortunately, the real chemistry and all the thermal and chemical constants are known for only some half-dozen fuel mixtures. A further misfortune is the fact that these half-dozen fuels included none of those important in practice. In fact, to get the flame speed right (± 10%), for the hydrogen–oxygen flame requires twenty reactions between eight species [39]. In fact, internal flame composition measurements [40] showed that practical cases involved many intermediate species and radicals, as well as ions and the corresponding — sometimes hundreds of — reactions. Thus, even today, fire calculations seldom go beyond a single Arrhenius reaction rate (eqn. (5)) in spite of the inherent improvements possible using more recent developments in chemical kinetics. For most useful fuels and fire problem materials, the chemistry is not yet known.

THE AWAKENING — ADMINISTRATIVE

I start with "administration", since No Money means No Research — Almost. A general awakening to the potentialities of science in application to fire problems occurred in a number of places. Japan and England each had a good national fire test laboratory, and they increased their scientific potential by their additions to staff. In 1951 at Borehamwood, England, they employed an Honours Degree recipient with a Ph.D from Cambridge University — our honored guest, Phillip Thomas.

In the United States the then FCDA (Federal Civil Defense Administration), in their concern for the ignition of a city by an atomic bomb, came to the National Academy of Sciences, and asked them to assemble a committee of scientists, engineers, and fire specialists to examine the civil defense fire problem and recommend what should be done. A committee was appointed under the chairmanship of Hottel.

A series of meetings was held in which combustion specialists, fire chiefs, fire bosses, and fire protection engineers discussed the fire problem: what was being done and what should be done. There was a clear division of interests and, indeed, understanding, between the science types and the practical fire types. In one early meeting, various groups showed their "research results". Only the arc imaging furnace ignition studies made at the Naval Radiological Laboratory [41] could be classed as fire science. Researchers there had used dimensionless variables to the degree that was possible. The fire fighters and fire protection engineers were already, in their daily work, doing everything that they and we (the scientists) knew how to do. What was badly needed as an essential basis for new fire safety ideas was a better understanding of fire; its ignition, growth, and extinguishment. In short, we needed fire science.

The Fire Research Committee prepared a small booklet recommending "A Fire Research Program for the United States". In general, these recommendations fell on polite but unreceptive ears. Randall Robertson, the associate director of NSF, was an exception, and he asked the Academy Fire Research Committee to request and screen some fire research proposals which NSF would then fund. In the late 1950's there was a lot of research money of all sorts from aeronautical and space sources, so that the effort to start new work failed for want of a sufficient number of good proposals.

The book *The Use of Models in Fire Research* [42] resulted from one of the conferences and brought together G. I. Taylor, Phillip Thomas (VII)*, a Ph.D. Fire Chief — G. Magnus, Professor at the Technisches Hochschule in Carlsruhe, Germany — and others, but had little effect on the amount of fire science actually carried out.

The next idea was the preparation of the journal *Fire Research, Abstracts, and Reviews.* Under the able editorship of Robert Fristrom, this publication, supported by NSF, the United States Forest Service, and the Civil Defense Administration, and distributed free to all interested parties by the National Academy of Sciences, performed a significant service. In 1967 when, on sabbatical, I visited fire research laboratories around the world, I never failed to find the FRAR on their library shelves.

Fire science progressed a bit during this period. The classic paper on plumes was published by Morton *et al.* [36]. Spalding [43] and Emmons [44] had presented experimental and analytical results showing the significance of Spalding's B number. Thomas was working on various fire problems of flame propagation over fabrics (II, V), flashover

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*Roman numerals refer to items in Phillip Thomas' Bibliography.

(I, III), extinguishment (IV), height of flames (V, X), self-heating (VI, VIII, IX, XI), and enclosure fires (VI, VII, XII). Kawagoe [45] had studied the flow through vents and introduced $A\sqrt{H}$ as a correlation parameter for fully developed fires.

The United States Forest Service in the meantime was developing its fire research program and had started its three fire research laboratories at Richmond, California; Macon, Georgia; and Missoula, Montana.

In 1962 the Fire Research Committee, with the support of the NSF, ran a one-month summer study at Woods Hole on the fire problem — both forest and urban. The result was a recommendation that a federal program starting at about $2,000,000 should be established [46]. The Bureau of Standards took up the suggestions and a bill, "The Fire Research and Safety Act of 1963", was introduced into Congress. This bill went nowhere. Professor Wiesner, then the Presidential Science Advisor, received three thousand letters and telegrams [47] from the stock fire insurance industry, the National Fire Protection Association, from fire chiefs and fire protection engineers, claiming that the bill was "Federal interference in private enterprise", and that "We are already doing all the research that is relevant". Both arguments were false.

The bill was dead, but NSF continued to support all the good fire research proposals they received. Fire science grew apace. In 1964 the Combustion Symposium included Sessions on fire for the first time. There were twelve papers on various fire subjects. Thomas, Baldwin and Heselden presented "Buoyant Diffusion Flames — Some Measurements of Air Entrainment, Heat Transfer, and Flame Merging".

At about this time the Factory Mutual System management considered the possible costs and benefits of a program to develop a better understanding of all aspects of fire, and in 1964 started their now well known and productive programs in basic and applied fire research.

By 1968 the various groups opposed to any change in Federal support of fire research had reconsidered their position, so that the Fire Research and Safety Act of 1968 passed Congress with strong support from the Factory Mutual System, and a neutral position by most of the previously opposing groups. This Act charged the National Bureau of Standards with responsibility for the technical aspects of the national fire problem, and directed the President to establish a special Presidential Commission to study the fire problem and recommend actions.

The fire program at the National Bureau of Standards was expanded, eventually becoming what we know today — a well balanced fire research program containing an appropriate fraction of fire science.

The Presidential Commission recommended in 1972, in their report "America Burning," [48] that, among other things, a Fire Administration be established in the Department of Commerce, that a Fire Academy be established by the new Administration, and that technical basic and applied research be supported with a budget of $25,000,000 per year. As you know, a Fire Administration was set up, an effective Fire Academy is slowly coming into existence, and the technical work, basic and applied, at NBS has increased; but only to about one quarter of that recommended.

In 1973 the Federal Trade Commission settled a class suit against the entire plastics industry of the United States, among other things, securing agreement to set up a million dollar per year fund to sponsor research on the fire-safe use of cellular plastics. The nine member committee (four industry members, five public members) supported a program of fire research with a balance of fire science and its applications. The Products Research Committee's task and funds ended on December 31, 1979, so that the support for fire research has just shrunk by one million dollars per year. Since the NBS external research program has remained at about two million dollars for many years, the decrease in grant funds is about one third (not counting inflation).

THE AWAKENING — ACCOMPLISHMENTS

A detailed listing and technical evaluation of all that has been accomplished is impossible in what space is left in this paper. A number of reviews and a few books have recently appeared [49 - 54] and we will here have to be satisfied with only a few observations.

The classical plume work by Morton *et al.* [36] has been extended in several directions. The plume out the window which often spreads a fire upward has been studied by Yokoi [55] (XXX) while Faeth [56] has studied a fire plume along a wall, and in the corner of a room. The entrainment by a hot plume issuing from a door into a next room is just now being considered [57].

The most important fire fuel is a solid (wood or plastic). Except for charcoal, solids don't burn. They must first pyrolyze. Following the work on radiation pulse ignition [41], the species present in the gaseous pyrolysis products have been shown to be generally very numerous and related in a complex way [58, 59] to exactly how the pyrolysis occurs. The complexity is, in fact, so great that for now and the near future, fire theorists can't expect to understand the real chemistry involved. The treatment of the dynamics of pyrolysis of a charring solid, as now analyzed, assumes, at most, a single Arrhenius (eqn. (5)) charring reaction.

Smoldering studies are progressing slowly [60, 61]. It appears that interacting chemical and thermal rates are essential here, as in ignition processes.

When the gases thus released are burned in air, the boundary layer burning [43, 44] or plume burning [62, 63] is partially understood. However — again — the chemistry is covered by, at most, one Arrhenius reaction rate, and even this is often avoidable by use of the Shwab–Zeldovich transformation, when use is made of the fact that for most actively burning fires the actual burning rate controlling mechanism is diffusive rather than chemical.

However, there are major fire problems that are not wholly dynamic. The action of fire retardants [3] is probably wholly a chemical problem. Ignition [30, 64, 65], (VIII, IX, XI, XXXII) involves an intimate mix of chemical-rate-controlled heat release, and the dynamic heat loss mechanisms. A fire boundary layer of flame plume does not burn a fuel to completion. The soot and toxic gases left unburned [66], especially for burning in fire-vitiated air, is of major importance in controlling life loss, and is again probably a delicate balance between chemical reaction rates, radiation energy loss, and turbulent eddies.

Just as the chemical problems of fire are too difficult for the chemist, so the dynamic problems of turbulent flows of fire gases are too difficult for the dynamicists. In both cases progress is being made on various more or less workable approximations. Flame and smoke composition in simple terms, CO, CO_2, H_2O, $(CH_2)_x$, (C) is being measured [66]. Flow turbulence is being treated, in part, by correlation techniques [67] (VI, VII, XVIII) and, in part, by various analytical models [68, 69].

The gas dynamics accompanying a fire [77 - 79] are usually thought of as a hot plume, a hot gas layer in an enclosure, and a buoyant gas flow out of a vent [70]. There are other effects. If the enclosure is sealed, as in a P3 biolab, a hyperbaric chamber, or a space ship, even a small fire will raise the pressure to dangerous levels. The Apollo capsule was burst by the Apollo fire. If it is not sealed, a vigorous fire produces a vigorous flow throughout the structure. There are many subtle flow effects [71] not yet understood, although major effects such as ceiling jets [72], hot layer formation, and vent flow rates (XIII, XXXVI) are understood.

It is now known that in all but the smallest fires, the primary mechanism of pyrolysis rate control and fire spread is radiation from fire products. Much progress has been made, as reviewed by de Ris [50]. However, since a knowledge of soot and chemical species and of the average size and shape of flames is essential, much work remains to be done.

It is very rare these days that there is a structural collapse in a fire until a very late stage. This is basically because the science of structures and of thermal conduction permit both the reliable calculation of performance and the devising of adequate insulation of structural members based on definitive fire tests. There are, however, some important problems not yet resolved. The reaction of reinforced concrete to fire is complex [73], and spalling of concrete and stone [74] is still an unresolved problem. The thermal stress breaking of window glass is an almost untouched problem.

Several problems have only begun to attract careful scientific study. The production, aging, and distribution of smoke particulates [75] must eventually be known for health and fire detector placement effects.

The process of extinguishment has received almost no scientific study to date [76] (IV, XLIV), although much empirical study has resulted in improved fire fighting devices.

As we look to the future, we can see the gradual development of the complete scientific understanding of all the component processes that make up a fire. As usual, we must expect that some of these component processes will be too difficult to be handled in a practical way by computation from first principles, even though we may know how. Thus, handbooks of measured and correlated fire properties can be expected to grow to cover a vast array of needed data. These data will feed into appropriate Mathematical Models [77 - 80] of fire which are now in their infancy. These Mathematical Models will eventually serve to screen new materials for their fire-safe application, and will supplement fire codes by making a performance code possible.

Our respected guest, Phillip Thomas, has, over the years, made contributions to nearly every aspect of fire science. In addition, he has, by papers, lectures, and committee activities, shown how to use fire science to meet practical day-by-day fire problems (XII, XIX - XXV, XXVII - XXXI, XXXIV - XXXVII, XL - XLIII, XLV).

Although fire science has grown enormously over the past twenty years, there is still much to be done. An observation that Phil Thomas made at the Fourteenth Symposium (International) on Combustion in 1972 (XXXV) is still valid today:

"The development of fire technology is such that, for some time to come, there is going to be a considerable degree of empiricism. Tempting as it would be to disown this, the pressure from statistical and operational studies for simplified "laws" of fire behavior is growing and providing sound physical descriptions in quantitative term as inputs for such work, as well as for practical fire engineering, presenting a continuing double challenge to the combustion scientist".

LIST OF SYMBOLS

A	Stearic Factor
C_p	specific heat at constant pressure
D	diffusion coefficient
E	activation energy
h	enthalpy
k	thermal conductivity
M	molecular weight
p	pressure
Q	heat per unit volume per unit time
R	gas constant
S	flame speed
T	temperature
v	velocity component
W	mass created per unit volume per unit time
Y	mass fraction
δ_{ij}	Kronecker Delta $= \begin{cases} 0 \text{ if } i \neq j \\ 1 \text{ if } i = j \end{cases}$
μ	viscosity
ρ	density
τ	shear stress

Subscripts

,	indicates differentiation $T_{,t} \equiv \dfrac{\partial T}{\partial t}$
i, j, k	(= 1, 2, 3) indicates coordinate direction
i	ignition
f	final
o	initial
r	species
s	species
t	time

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